# 9 STRESS DUE TO ALKALI-SILICA REACTIONS IN MORTARS

C.F. FERRARIS, J.R. CLIFTON, E.J. GARBOCZI and F.L. DAVIS
National Institute of Standard and Technology, Gaithersburg, MD, USA

**Abstract**
Alkali-silica reaction (ASR) causing deterioration of mortars and concretes is due to the swelling of gel formed by the reaction of alkali in cement-based materials with reactive silica in aggregates, in the presence of water. The swelling of the gel generates tensile stresses in the specimen resulting in expansion and cracks. Most tests designed to detect ASR rely on measurements of the length change. A new test, designed to measure the stress generated by the swelling of the gel, has a cylindrical mortar specimen placed in a frame under a load cell. The force required to prevent expansion is measured over time while the sample and frame are immersed in a solution of 1 N NaOH at 50 °C. Along with the design of the apparatus, some preliminary results are presented. Measurements of stresses showed a strong influence of creep on the mechanical response of the material subjected to ASR. The aggregate influence on the stress and expansion due to the ASR was investigated.
Keywords: Alkali-silica reaction, mortar, stress measurements, Young's modulus, stress relaxation.

## 1. Introduction

Damage of concrete due to alkali-silica reaction (ASR) is a phenomenon that was first recognized in 1940 by Stanton [1,2] in North America. It has since been observed in many other countries. Many studies [3,4,5] have been published since Stanton's first paper, but the mechanisms of ASR are not yet clearly understood [6]. Nevertheless, the major factors have been identified. In the presence of water, alkalies in the pore solution react with reactive silica, found in certain aggregates. Related factors which can play a significant role are environmental relative humidity (RH), porosity of the concrete, and mineral admixtures in the concrete.

*Mechanisms of Chemical Degradation of Cement-based Systems*. Edited by K.L. Scrivener and J.F. Young. Published in 1997 by E & FN Spon, 2-6 Boundary Row, London SE1 8HN. ISBN: 0419215700.

Most methods in use today to detect ASR in mortars or concretes are based on measurements of the expansion of the sample. In this paper, we will describe a novel technique consisting of the measurement of the expansion stress generated by the reaction. The main advantage in measuring stresses instead of length changes is that the results might be able to be used to design a concrete that resists ASR expansion, i.e., with a tensile strength higher than the stress generated by the reaction.

## 2. Background

Most researchers agree that the main form of ASR is between certain kinds of silica present in the aggregates and the hydroxide ions ( $OH^-$) in the pore water of a concrete [3,4]. Hydroxide ions from the hydration of portland cement result in a pore solution pH of around 12.5 [7]. The amount of alkalies present in the pore water is related to the amount of soluble alkalies in the cement. The hydroxide ions may attack vulnerable sites exposed in a silica surface. If the silica is well-crystallized the vulnerable sites are few but in the case of poorly-crystallized or amorphous silica, there are many vulnerable sites in the silica structure; in the latter case, alkali attack may lead to complete conversion of the silica to calcium and alkali silicate gel [8,9]. To keep a neutral charge balance, the cations $Na^+$ and $K^+$ diffuse toward the hydroxide ions, producing a gel-like material.

The formation of the gel *per se* is not deleterious. The deterioration of the concrete structure is due to the water absorption by the gel and its expansion. If the tensile strength of the system is locally exceeded, cracks will form and propagate in radial fashion around the reaction site. The sites of crack initiation are randomly distributed in the specimen, and there is no preferential direction for cracks to propagate. The crack sites are determined by the location of the reactive silica on the aggregates and the local availability of $OH^-$.

Most tests available for detecting ASR in concrete are based on measurement of the specimen expansion. The mix design and the condition of testing differs among tests. There are three ASTM tests currently used: ASTM C1260 [10] , ASTM C227 [11], and ASTM C441 [12]. Other tests described in the literature are usually modifications of the above tests. A German test [13, 14] was developed to measure the stress generated from ASR but limited data are available. Recently, Sellier et al. [15] attempted to simulate the stresses and the swelling due to ASR and found good agreement with available measurements. We used a mix design that simulates high performance concrete, with low permeability, low water/cement ratio and high cement content.

## 3. Experimental Set-up

### 3.1 Stress measurements

A novel test was designed to measure the stress generated by ASR in mortars. Figure 1 shows a sketch of the apparatus. The specimen, a mortar or concrete cylinder, is placed in the stainless steel frame and connected to a load cell. The load cell, connected to a computer, monitors, at regular intervals, the force generated by the formation of the ASR gel and the specimen expansion. To guarantee that the load cell response (voltage) is uniquely related to a force generated by the specimen, the cell

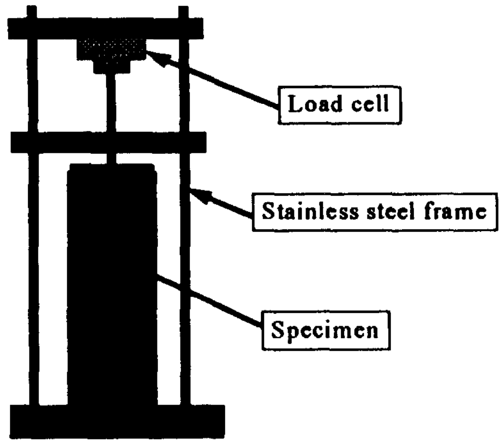


Figure 1: Schematic view of the device used to measure stress due to ASR.

was calibrated, using a dead weight set-up, in the same configuration (frame) as it was used during the experiment.

The frame holding the specimen is immersed in a container with a 1N aqueous solution of NaOH which is the test solution used in ASTM C1260 [10]. The container is then placed in a water bath with a controlled temperature of 50 °C ± 3 °C. The effect of differential thermal expansion between the sample cylinder and the steel legs of the frame was found to be unimportant. Since the experiment was conducted at constant temperature, the initial thermal expansion was easily taken into consideration.

### 3.2 Specimen preparation

In this initial study, only mortar specimens were tested. Three specimens were prepared for each mix. Table 1 gives the mixture designs used, while Table 2 gives the sand gradation. One sand was selected for its reactivity and one for its lack of reactivity with alkalies.

The specimens were cylinders 38 mm in diameter and 279 mm long (1.5 in. x 11 in.). The cement used had a high alkali content (about 1.2 % $Na_2O$ equivalent). As the high alkali content of the cement should result in a high alkali concentration and pH in the pore solution, this cement should promote ASR with reactive siliceous aggregates. Companion cylinders were also placed either in limewater or in 1 N NaOH solution for unrestrained expansion measurements. All the samples were kept at 50 °C ± 3 °C.

Table 1. Mixture design of the mortars

| Mixture design | Mix A | Mix B |
|---|---|---|
| Water/Cement | 0.295 by mass | 0.295 by mass |
| Sand/Cement | 1.411 by mass | 1.411 by mass |
| Type of sand | Tecosil[1,3] | U.S. Silica[3] |
| Sand Gradation | Gradation #1 (Table 2) | Gradation #2 (Table 2) |
| HWRA[2] | HRWA #1 @ 0.50% by mass of cement | HRWA #2 @ 4% by mass of cement |

Table 2. Mortar sand gradation

| Gradation simulated | Sand Size range Sieve size ASTM E11 | Dimension [μm] | Mass [%] |
|---|---|---|---|
| #1 | 4-10 | 4750-2000 | 15 |
| all sands are from | 10-20 | 2000-850 | 35 |
| Tecosil[3] | 20-50 | 850-300 | 25 |
| | 50-100 | 300-150 | 25 |
| #2 | S15 | 2360-600 | 35 |
| all sands are from U.S. | C778 (20-30) | 850-600 | 19 |
| Silica[3], Ottawa Illinois. | C778 (Graded sand) | 600-300 | 19 |
| | F95 | 300-200 | 25 |
| The sand gradation was selected as a simulation of a smooth size distribution (not gap graded) | | | |

## 4. Results and discussion

Figure 2 shows the stress-strain plots for the two mixes. The strain was measured in the free expansion samples, while the stress was measured for the samples confined by the frame. For Mix A, the stress increased rapidly with strain, and then increased much more slowly. This phenomena is attributed to the occurrence of cracking, which accompanied the large degree of expansion shown by this mix. The stress for Mix B was always fairly linear with the expansion strain. If we fit a straight line to the stress-strain graph for Mix B, the "apparent" Young's modulus value obtained is E=3.3 GPa, with an $R^2$ of 0.86. This value is low by about a factor of 10 compared to concrete or mortar, which usually has a value of E in excess of 30 GPa [16]. For Mix A, since the measured strain in the unrestrained linear expansion specimen consisted mostly of crack opening displacement, the expansion of the cylinder after being removed from the frame was divided into the measured stress to give an estimate of

[1] Graded sand provided by C-E Minerals[3], PA USA. The composition is fused silica (amorphous)

[2] by mass of cement; HWRA #1 was supplied by W.R Grace and Co[3]. while HRWA #2 was supplied by Masters Builders[3]

[3] The name of manufacturers are identified in this report to adequately describe the experimental procedure. Such an identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material identified is necessarily the best available for the purpose.

the "apparent" Young's modulus. There was no apparent cracking in this case. The result was nearly the same as that obtained for Mix B. If the strain for Mix B is measured after releasing from the frame an "apparent" Young's modulus of about 18 GPa is obtained. This results seem to confirm the simulation presented by Sellier et al. [15].

Consider now the role of stress relaxation. Suppose the mortars were only linearly elastic. We could then treat the mortar as an elastic composite, which had a small volume fraction of material (ASR gel) that exerted internal stresses by trying to occupy a larger space. The measured stress would then be the effective modulus of the mortar/gel composite multiplied by the measured strain. In this case, for Mix B for example, the measured stress should have been 30 MPa, not 3 MPa, and large scale cracking should have been seen. Similar results should have been obtained for Mix A, when considering the expansion of the cylinder after being released from the frame. This large discrepancy between experimental results and those predicted by linear elasticity implies that stress relaxation played a large role in this experiment in addition to crack opening displacement in Mix A. This finding is in general agreement with the results and conclusion obtained by Stark [17]. Clearly, as the alkali-silica reaction went forward, producing expansive gel, the mortar was able to rearrange itself, thereby relaxing the longitudinal stress to the levels seen. Part of this rearrangement would show itself in lateral movement (bowing and/or increase in diameter), which was indeed observed on the samples. It is known that early-age concrete creeps much more than late age concrete, and since the ASR test started at only 24 hours of hydration, stress relaxation could clearly play a major role. This seems to be the only explanation of the samples' mechanical behavior. Plans have been made to check this explanation by putting an initial compressive stress on a 24 hour old non-reactive aggregate sample, and then measuring the change of stress with time as stress relaxation occurs during the ensuing hydration. However, the problem of stress relaxation induced by internal stresses has not previously been considered theoretically, and is worthy of further investigation.

The two different aggregates had very different effects on the level of the measured expansion and stress. The total free expansion of Mix A was about 10 times greater than that of Mix B (Figure 3). As only the type of aggregates differed, these plots indicate that sand #1 is more reactive than sand #2. However, the stresses

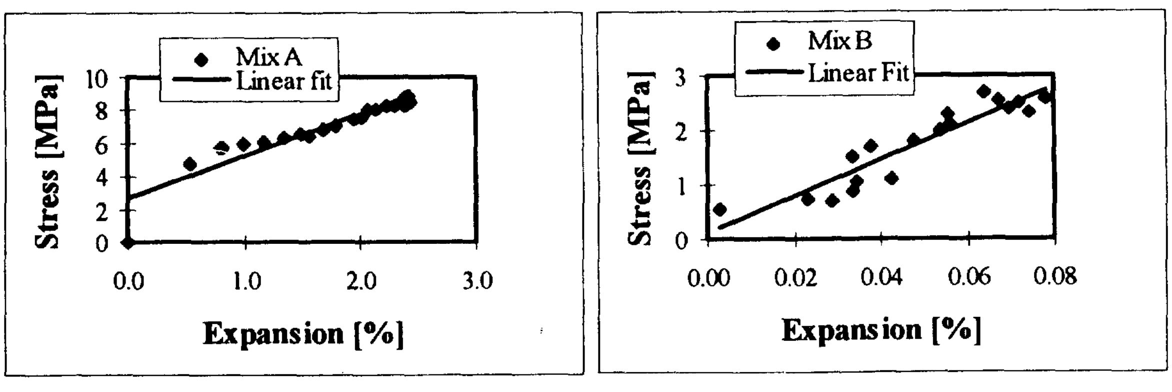


Figure 2 Stress-expansion plots for mortar specimens in NaOH solution at 50 °C.

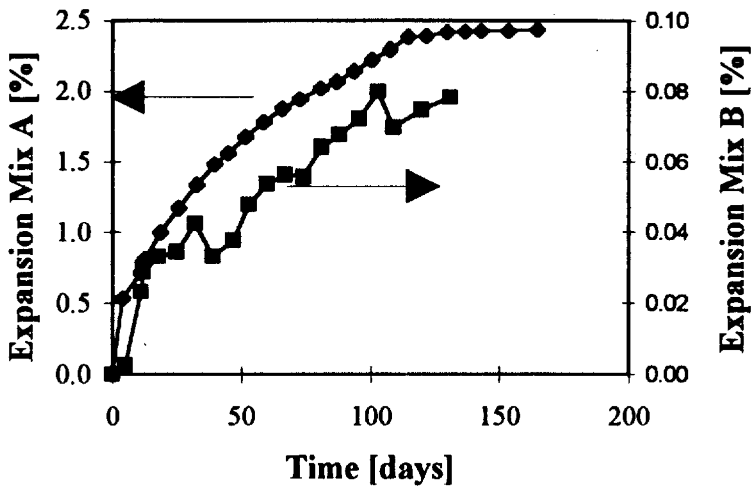


Figure 3 Expansion measurements on the tested mortar.

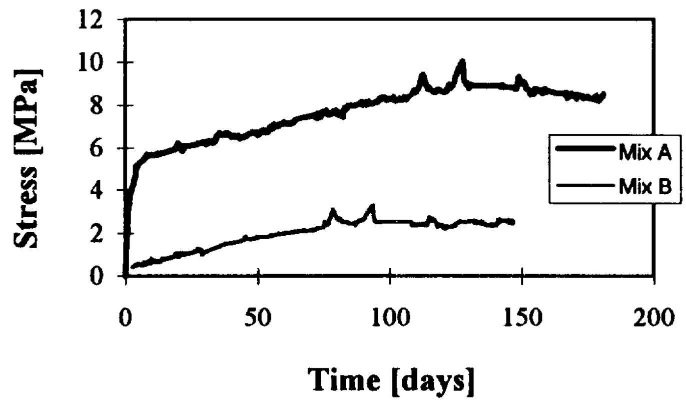


Figure 4 Change of stress with time for the constrained specimens.

measured were not much different (Figure 4). This result is interpreted in the following way. The internal stresses in the Mix A sample were able to build up enough so that the tensile strength was exceeded locally, producing the large number of lateral cracks and the large linear expansion seen. The internal stresses in the Mix B sample never exceeded the local tensile strength, so only a small expansion was seen. The actual stresses produced could be similar, however, for as long as the stresses in Mix B stayed below the tensile strength, and the stresses in Mix A exceeded the tensile strength, a large difference in the free expansion would be seen. The amount of gel produced in the two samples will be measured in the scanning electron microscope to determine the actual difference in reactivity between the two aggregates.

## 5. Conclusions

It has been shown, using the new apparatus, that the substantial forces exerted by ASR can be measured, once the role of stress relaxation was made clear. It now will be possible to study factors affecting the forces for different materials and mixture properties, environmental conditions, and specimen geometries so as to provide data for mixture design and calculation of constrained expansion due to ASR in actual structures.

## 6. Acknowledgments

This work was sponsored by the "High Performance Construction Materials and Systems" program at NIST. Support for this work was also obtained from the Nuclear Regulatory Commission (NRC). John Winpigler is acknowledged for performing the measurements.

## 7. References

1. Stanton, T. E. (1940) Expansion of Concrete Through Reaction Between Cement and Aggregate, *Proc. of the American Soc. of Civil Eng.* Vol. 66, #10, p. 1781-1811.
2. Frohnsdorff, G., Clifton, J., Brown, P., (1979) *History and Status of Standards Relating to Alkalies in Hydraulic Cements,* Special Technical Publication 663, ASTM, p 16-34.
3. Hobbs, D.W., (1988) *Alkali-Silica Reaction in Concrete*, Thomas Telford, London.
4. Diamond, S., Penko, M., (1992) Alkali Silica Reaction Processes: The Conversion of Cement Alkalis to Alkali Hydroxide ,G. M. Idorn Inter. Symposium, *Durability of Concrete* ACI SP-131, American Concrete Institute.
5. Helmuth R., (1993) *Alkali-Silica Reactivity: An Overview of Research*, SHRP Report C-342. National Research Council, Washington DC.
6. Capra, B., Bournazel, J.-P., (1995) Perspective nouvelles pour la prise en compte des alcali-reactions dans le calcul des structures, *Materials and Structures*, vol. 28, p. 71-73.
7. Diamond, S., (1983) Alkali Reactions in Concrete Pore Solutions Effects, Proc. 6th Int. Conf., *Alkalis in Concrete*, Idorn G.M. and Rostam S. eds., p. 155-166. Danish Concrete Association.
8. Figg, J., (1983) "An Attempt to Provide an Explanation for Engineers of the Expansive Reaction between Alkalis and Siliceous Aggregates in Concrete", 6th Int. Conf. *Alkalis in Concrete*, Copenhagen.
9. Helmuth, R., Stark, D., (1992) Alkali-Silica Reactivity Mechanisms in *Materials Science of Concrete III*, J. Skalny ed., American Ceramic Society. Westerville OH.
10. ASTM . (1994) *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method),* ASTM designation C1260-94, Annual Book of ASTM Standards Vol. 04.02.
11. ASTM. (1994) *Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method),* ASTM designation C227-90, Annual Book of ASTM Standards Vol. 04.02.

12. ASTM. (1995) *Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction*, ASTM designation C441-89, Annual Book of ASTM Standards Vol. 04.02.
13 Kuhlman J., Lenzner D., Ludwig V. (1975) A Simple Method of Measuring Expansion Pressures, Zement-Kalk-Gips 28-12, p. 526-530
14 Lenzner D. (1981) *Untersungen zur Alkali-Zuschlag Reaktion mit Opalsandstein aus Schleswig-Holstein*, Thesis from Rheinisch-West falischen Technischen Hochschule Aachen.
15 Sellier, A., Bournazel, J.P., Mebarki, A., (1995) Une modelisation de la reaction alcalis-granulat integrant une description des phenomenes aleatoires locaux, *Materials and Structures,* vol. 28, pp. 373-383
16 Gutierrez, P.A., Canovas, M. F., (1995) The Modulus of Elasticity of High-Performance Concrete, *Materials and Structures,* Vol. 28, pp. 559-568
17 Stark, D., Morgan, B., Okamoto, P., (1993) *Eliminating or Minimizing Alkali-Silica Reactivity,* SHRP-C343, National Research Council, Washington DC.